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WIND AND RADIATION

By W. J. HUMPHREYS

[Washington, D. C., December 1938]

Naturally, one might suppose that, in general, the radiative loss of heat by the surface of the earth and lower air on clear nights must be the same whatever the wind, calm to gale. It is true that the perviousness of the air to all radiation, ultraviolet, visible, and ultrared, is the same regardless of its motion. Therefore, if everything else were the same, the losses of heat would be equal in the two cases under consideration; but they are not the same, for the temperatures of the surface and of the lower air are affected by the strength of the wind. Where the air is calm the supply of heat to the cooling surface, apart from that conducted up from below, comes from only a very thin layer of the superjacent air, whereas on windy nights it comes, owing to turbulence, from a much deeper layer of this air. Hence, from that cause alone, the surface would be warmer on a windy night than it would have been if the air had been calm. There is also another effect of the wind to take into account that still further increases this temperature difference, namely, the complete mixing of the air of the turbulent layer, by which it is brought to a common potential temperature—its lapse rate made adiabatic instead of being left subadiabatic—and the surface air thus brought to a higher temperature than it would have if calm.

Obviously, then, the surface of the earth and the adjacent air must be, and they are, colder during calm nights than on windy nights. But the loss of heat by radiation from the surface of the earth (practically a full radiator) varies closely as the fourth power of its absolute temperature. Hence, in general, on clear nights the earth radiates a greater quantity of heat when there is a strong wind than it does when the air is calm, but does not come to as low a temperature.

MINIMUM TEMPERATURES DURING SPRING AND AUTUMN AT LINCOLN, NORTH PLATTE, AND SCOTTSBLUFF, NEBR.

By HARRY E. HOY

[University of Illinois, Urbana, Ill., June 1938]

INTRODUCTION

The purpose of this study[1] is to determine the minimum temperatures during the transition periods of spring and autumn at three selected stations in Nebraska. The latest date of freezing temperature ever recorded at Lincoln is May 15 (1907); but the fact that a killing frost has never occurred after this date is not evidence that one never will. The writer, by a detailed study of the 39 or more minimum temperatures for each date, has attempted to determine what the probability of a killing frost is for each day, from reasonable frost-certain to reasonable frost-free dates during spring, and from frost-free to frost-certain dates in autumn.

It is generally known that killing frosts occur on the majority of March days in Nebraska. As spring progresses the occurrences of freezing temperatures become less frequent, so that by June 1, the temperature rarely falls below 32° F. The three stations chosen are representative of the eastern, central, and western parts of the State. Since altitude is a more important modifier of growing season in Nebraska than latitude, an east-west line of stations was believed more desirable than a north-south line. The stations have kept continuous records for periods of 39 to 45 years. The three stations are about equally separated from each other by both altitude and latitude. Scottsbluff at altitude 3,888 feet is the northernmost, latitude 41°50′ N. North Platte, altitude 2,821, is at latitude 41°10′; Lincoln, altitude 1,189, is located at latitude 40°41′. Scottsbluff experiences temperatures and amounts of precipitation which are about the lowest in the State; North Platte's are slightly below the average; at Lincoln they are slightly below the State maximum.

A killing frost is interpreted in this paper to mean a temperature of 32° F. or below, since in a statistical study it is felt that an objective definition of killing frost is more desirable for comparing conditions at different stations and at different times. This results occasionally in small differences between the dates of first and last killing frosts published by the United States Weather Bureau and the dates used in this study. The determination of a killing frost using the presence of frost crystals with freezing destruction to certain plants as indicators is no doubt of more practical importance to growers than is a temperature of 32° F. However, the unavoidable subjective element where several different observers report with different plants as indicators and at different times in the season, although perfectly defensible from a practical point of view, might be a bit indefinite in a statistical paper such as this. Both definitions are recognized as acceptable. Therefore, "freezing temperature" and "killing frost" will be terms used synonymously hereafter in this paper.

[1] See also Earl E. Lackey: Variability Isocrymal Maps for the Great Plains. MO. WEA. REV. 64: 70-76, March 1936.

Statistical methods are employed in organizing and applying the data used. All computations are based on the actual minimum temperatures for each day as compiled by the United States Weather Bureau. It was assumed that the distribution of 40 or more minimum temperatures for a given date would closely approximate a normal curve. This was borne out by later investigation. First, the standard deviation or the temperature range expected 68 percent of the time was determined. This was found by the application of the formula:

$$\text{Standard deviation}=\sqrt{\frac{\Sigma T^2}{N}-A^2}$$

where T is minimum temperature, N is the number of observations, and A is the average minimum temperature. By means of the standard deviation the following results were obtained for each date during the 6 months at Lincoln, North Platte, and Scottsbluff:

1. Average minimum temperature.
2. Limits of standard deviation.
3. Probability of a freezing temperature.
4. Lowest temperature expected 1 and 2 percent of the time. In addition to these, two other sets of data were worked out which also served as a check on the mathematical method used. They are (1) the lowest recorded temperature and (2) the probability of a frost after any date in spring and before any date in autumn. The lowest temperature expected 2 percent of the time would mean in the case of the data used, which covers about 50 years, a single occurrence of that temperature during the period. The lowest recorded temperature on that date bears out this assumption very well. Only in relatively few instances does the lowest recorded temperature vary more than 3° or 4° from the temperature expected, on the average, 1 year in 50. The averages of the lowest temperatures recorded and the lowest expected 2 percent of the time, are nearly identical.

CONDITIONS AT LINCOLN

Lincoln was selected as representative of the eastern part of Nebraska. Here the frost-free period is nearly as long as that found anywhere in the State. The transition periods between winter and summer, and summer and winter, are earlier in spring and later in autumn than at the other two stations. With reference to figure 5 (graph showing spring conditions of minimum temperature in Lincoln, Nebr.) it is seen that the average minimum temperature ranges from 20.7° F. on March 1, to 34° F. on April 1, to 45° F. May 1, to 55° F. on May 31. While this general climb is taking place, there are many small irregularities. It is believed that a 46-year record is not long enough to smooth out all of the irregularities that might be caused by one or two extremely high or low minima.

The irregularities of day-by-day temperature change in autumn are less severe than are those of spring. The average daily drop is greatest in September and least in November; the opposite is true in spring, when March has the most rapid and May the least rapid rise. The average rate of daily increase in spring is 0.375° while the average daily decrease of autumn is 0.416°.

The limits of standard deviation are greatest early in spring and late in autumn because of the greater extremes of temperature that occur near the winter season. From March 1 to March 25 the average deviation is from 10° to 12°. After March 27 and until May 25 the usual deviations are about 8°. The usual deviation after May 25 is less than 7°. The table below illustrates the average standard deviations by months and by seasons.

Month	Average standard deviation	Month	Average standard deviation
	°		°
March	10.25	September	9.27
April	8.53	October	9.34
May	7.29	November	9.02
Average (spring months)	8.66	Average (autumn months)	9.21

The probability of a freezing temperature on March 1 is 85 percent. This high probability becomes gradually less until by April 1 it has dropped to 40 percent. On April 15 the probability is 16 percent, 10 percent on May

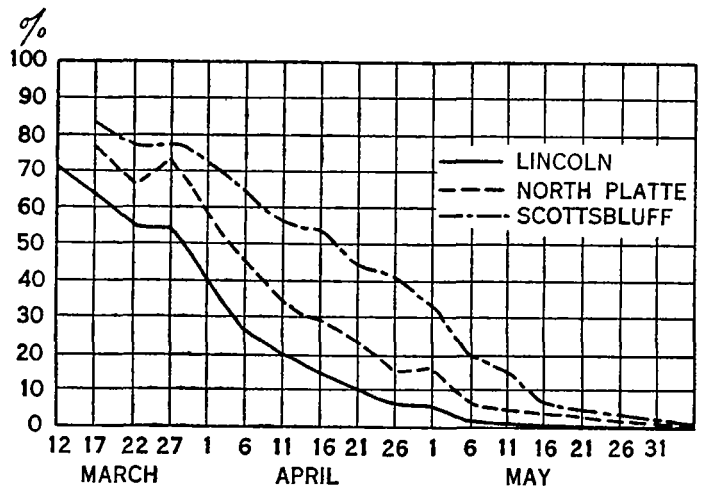

FIGURE 1.—Probability of a freezing temperature during spring. (Probabilities on dates indicated have been averaged with those of the dates on either side.)

1, and by May 15 only 1 percent. On May 31, the last day shown on the graph, the probability is less than 0.05 percent or a probable occurrence of about once in 2,000 years.

During autumn the probability of frost occurrence is only once in 10,000 years on September 1 but on September 15 the probability is 1 percent; October 1, 3.5 percent; November 1, 33 percent; and November 30, 80 percent. Figures 1 and 2 illustrate the decrease and increase,

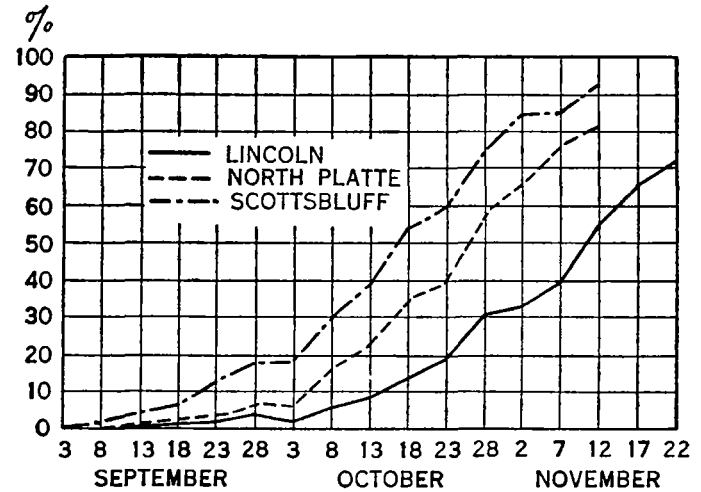

FIGURE 2.—Probability of a freezing temperature during autumn. (Probabilities on dates indicated have been averaged with those of the dates on either side.)

respectively, of frost probability in spring and autumn at Lincoln, North Platte, and Scottsbluff.

TABLE 1.—*Probability of a killing frost after any date in spring at Lincoln*

Date	Percent probable	Date	Percent probable	Date	Percent probable
Mar. 25	99.5	Apr. 14	67.0	May 4	8.6
Mar. 26	99.3	Apr. 15	63.7	May 5	7.2
Mar. 27	98.9	Apr. 16	60.3	May 6	6.1
Mar. 28	98.5	Apr. 17	56.8	May 7	5.1
Mar. 29	98.1	Apr. 18	53.2	May 8	4.2
Mar. 30	97.6	Apr. 19	49.6	May 9	3.4
Mar. 31	96.4	Apr. 20	46.1	May 10	2.8
Apr. 1	95.5	Apr. 21	42.5	May 11	2.3
Apr. 2	94.7	Apr. 22	39.0	May 12	1.8
Apr. 3	93.7	Apr. 23	35.5	May 13	1.5
Apr. 4	92.5	Apr. 24	32.2	May 14	1.2
Apr. 5	91.2	Apr. 25	29.1	May 15	.9
Apr. 6	89.6	Apr. 26	26.1	May 16	.7
Apr. 7	87.7	Apr. 27	23.2	May 17	.5
Apr. 8	85.9	Apr. 28	20.5	May 18	.4
Apr. 9	83.7	Apr. 29	18.1	May 19	.3
Apr. 10	79.0	Apr. 30	15.8	May 20	.2
Apr. 11	76.3	May 1	13.7	May 21	.2
Apr. 12	73.4	May 2	11.8	May 22	.1
Apr. 13	70.3	May 3	10.1	May 23	.1

TABLE 2.—*Probability of a killing frost before any date in autumn at Lincoln*

Date	Percent probable	Date	Percent probable	Date	Percent probable
Sept. 7	0.1	Oct. 1	14.2	Oct. 24	79.1
Sept. 8	.1	Oct. 2	16.1	Oct. 25	81.6
Sept. 9	.2	Oct. 3	17.9	Oct. 26	83.2
Sept. 10	.3	Oct. 4	20.5	Oct. 27	85.1
Sept. 11	.4	Oct. 5	22.8	Oct. 28	87.0
Sept. 12	.5	Oct. 6	25.3	Oct. 29	88.6
Sept. 13	.6	Oct. 7	28.0	Oct. 30	90.0
Sept. 14	.7	Oct. 8	30.8	Oct. 31	91.5
Sept. 15	.9	Oct. 9	33.7	Nov. 1	92.8
Sept. 16	1.1	Oct. 10	36.7	Nov. 2	93.3
Sept. 17	1.4	Oct. 11	39.8	Nov. 3	94.9
Sept. 18	1.7	Oct. 12	43.0	Nov. 4	96.2
Sept. 19	2.1	Oct. 13	46.2	Nov. 5	96.8
Sept. 20	2.5	Oct. 14	49.4	Nov. 6	97.3
Sept. 21	3.0	Oct. 15	52.6	Nov. 7	97.8
Sept. 22	3.6	Oct. 16	55.9	Nov. 8	98.2
Sept. 23	4.3	Oct. 17	59.1	Nov. 9	98.3
Sept. 24	5.1	Oct. 18	62.2	Nov. 10	98.5
Sept. 25	6.0	Oct. 19	65.2	Nov. 11	98.8
Sept. 26	7.0	Oct. 20	68.2	Nov. 12	99.0
Sept. 27	8.2	Oct. 21	71.0	Nov. 13	99.2
Sept. 28	9.5	Oct. 22	73.7		
Sept. 29	10.9	Oct. 23	76.4		
Sept. 30	12.5				

The two broken lines on the plates represent the temperatures expected 2 percent and 1 percent of the years on that date. These values are statistical probabilities

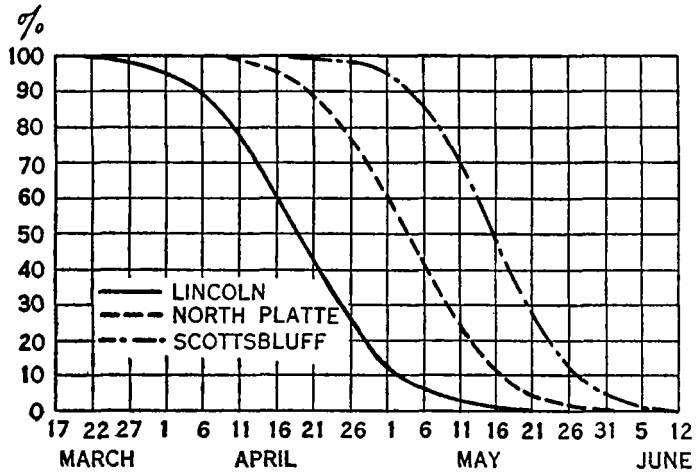

FIGURE 3.—Probability of a killing frost after each date in spring at Lincoln, North Platte, and Scottsbluff.

based on the standard deviation for that date. A standard deviation greater or less than the usual deviations causes the 1- or 2-percent probability points to be too low or too high respectively. A study of those lines as a whole is more valuable than the individual day-by-day values.

As might be expected the range of minimum temperatures is greatest in early spring and late autumn. The average range between the average minimum temperature and the average lowest recorded temperatures in March is 26° while that of May is 16.2°. In September the average variation is 17.3° and in November 22.2°.

March 15 is so early in the spring that a killing frost is expected to occur several times before summer, while the probability of a frost after May 31 is practically zero. The probabilities of frost after each date in spring and before each date in autumn are given in tables 1 and 2. This theoretical probability is determined by the use of the normal distribution curve applied to the dates of the first and last killing frosts. The earliest last killing frost of spring ever recorded is March 27 (1925) and the latest May 15 (1907). The probabilities of having a freezing

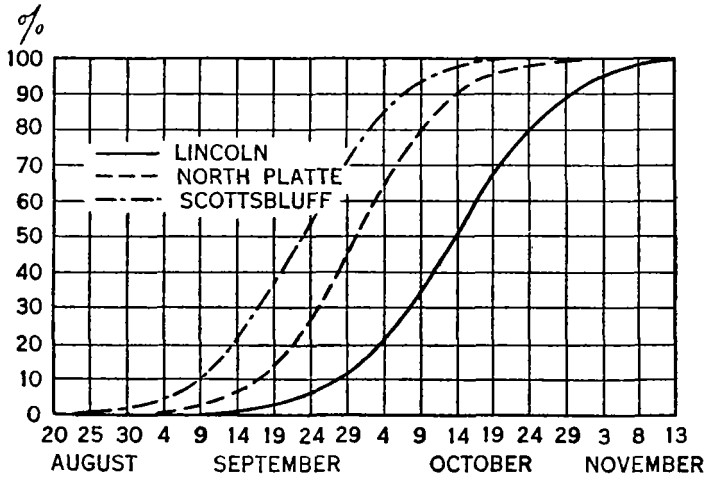

FIGURE 4.—Probability of a killing frost before each date in autumn at Lincoln, North Platte, and Scottsbluff.

temperature after these dates are 98.9 percent and 0.9 percent respectively. The dates of the earliest and latest recorded killing frosts of autumn are September 18 (1901) and November 7 (1924). The interval between the earliest and the latest last killing frost in spring is 49 days while the same interval between the earliest and latest first killing frost in autumn is 50 days. Actually as well as statistically 68 percent of the last and first freezes are clustered within 11.5 days of the average last and first killing frost dates, which are April 18 and October 17, respectively. Thus the average frost free season is 179 days. The limits of standard deviation of the last killing frost in spring are between April 9 and April 30 and of the first in autumn between October 2 and October 26. This means that there is less than a 16 percent chance that a last killing frost will occur before April 9 and after April 30 or that the first freeze of autumn will occur only 16 percent of the time before October 2 and after October 26. The shortest actual growing season ever recorded is 150 days (1907) while the longest is 219 days (1924). It is fortunate that the large majority of last and first killing frosts occur near the average data. This makes possible a fuller use of the growing season by crops requiring a long period for growth.

COMPARISON OF THE THREE STATIONS

The same study was made of the minimum temperatures at North Platte and Scottsbluff as at Lincoln. The same conditions as above interpreted for Lincoln are illustrated by figures 7, 8, 9, and 10. A brief summary will suffice to make a comparative study of the three stations possible. The periods studied at North Platte and Scottsbluff extended from March 15 to June 15 and August 15 to November 15. Similar temperature conditions occur about 15 days earlier in spring and 15 days later during autumn at Lincoln than at North Platte. During the period from March 20 to May 31 the average minimum temperatures increase from 29° to 55° at Lincoln, from 25° to 50° at North Platte, and from 24° to 47° at Scottsbluff. During autumn the approach of winter occurs earliest at Scottsbluff. Freezing temperatures occur 2 weeks earlier at North Platte, and from 3 to 4 weeks earlier at Scottsbluff, than at Lincoln.

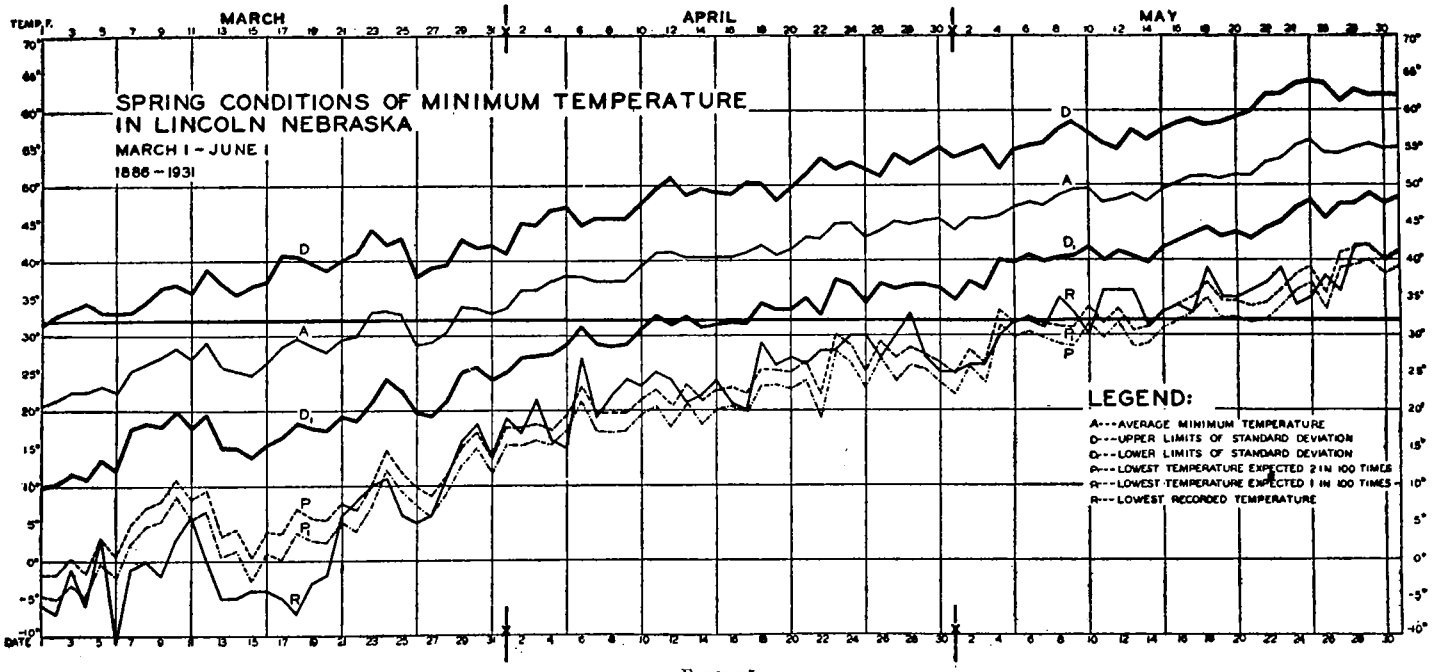

FIGURE 5.

The least variation between the lowest recorded temperatures and the average minimum temperatures occurs at Scottsbluff and the greatest variation at Lincoln. March and November extremes vary the most at all stations. The greater variation at Lincoln is reflected in the greater standard deviation found there. The spring season average shows an 8.68° variation at Lincoln, 7.70° at North Platte, and 7.71° at Scottsbluff. The autumn average standard deviations in the same order are 9.24°, 7.34°, and 7.05°.

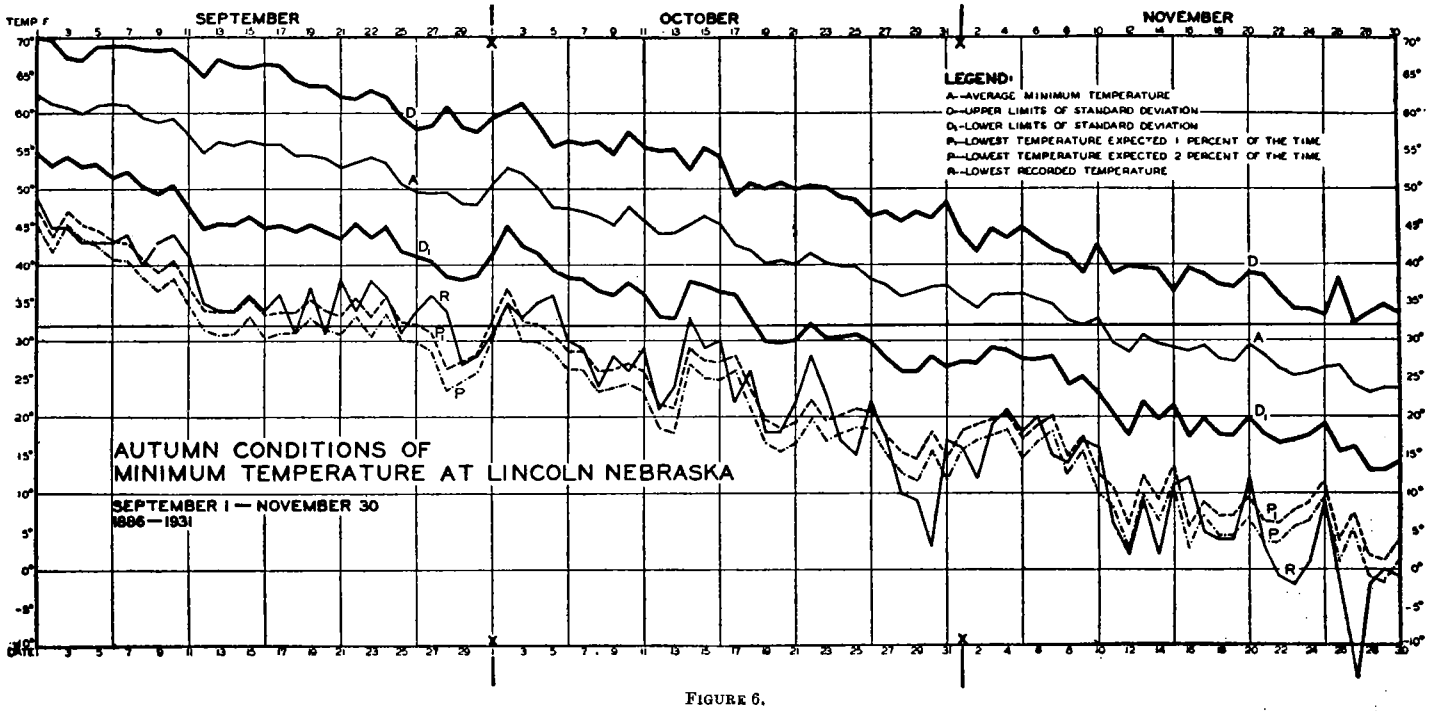

FIGURE 6.

The approach of summer and winter is slightly more rapid in the east than in the west. The average daily change of average minimum temperatures at Lincoln is 0.375° in spring and 0.416° in autumn, while the same change at Scottsbluff is 0.365° and 0.376°, respectively.

The probability of a freezing temperature during spring and during autumn at the three stations is illustrated by figures 1 and 2. The rate and time of advance of summer and winter are clearly distinguished at each point. For example May 15 at Lincoln is a fairly safe time to place fragile plants out of doors because the probability of a freezing temperature is less than 1 percent. At North Platte a freezing temperature can be expected over 16 percent of the time while at Scottsbluff the chances of frost damage would be great, as more than half the years have experienced a killing frost after May 15.

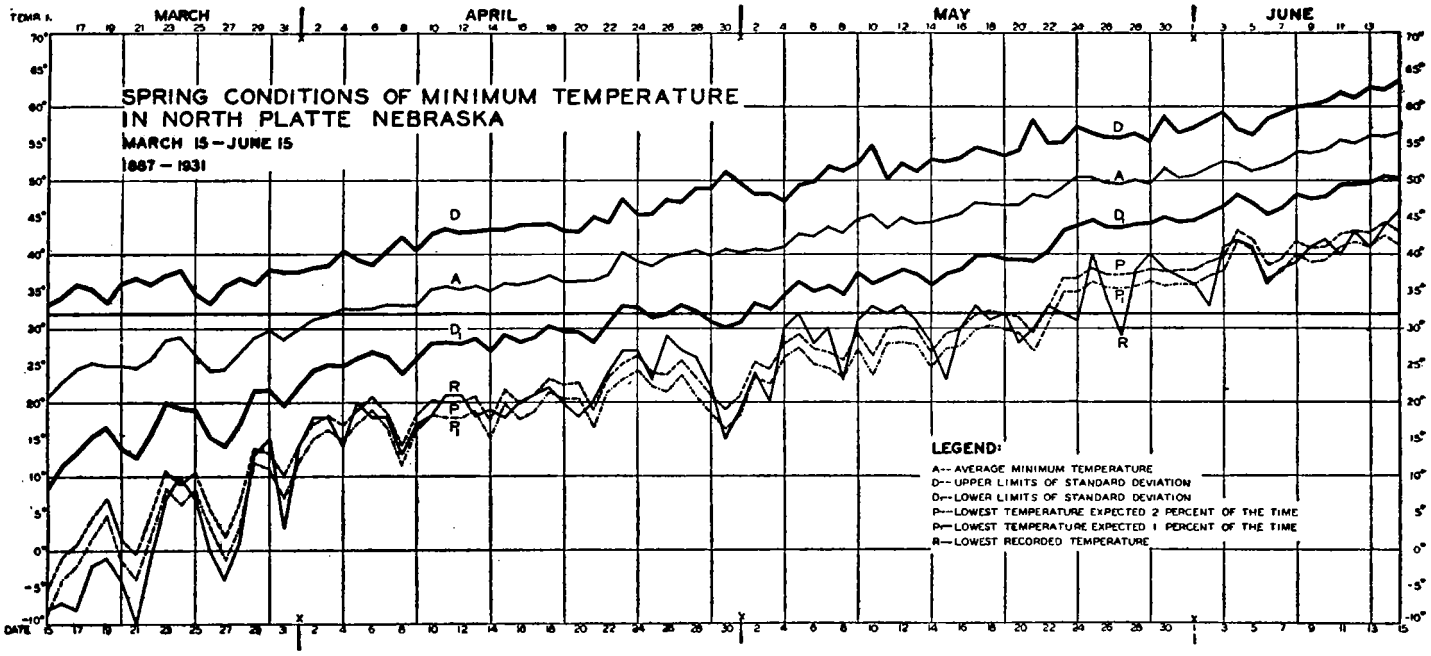

FIGURE 7.

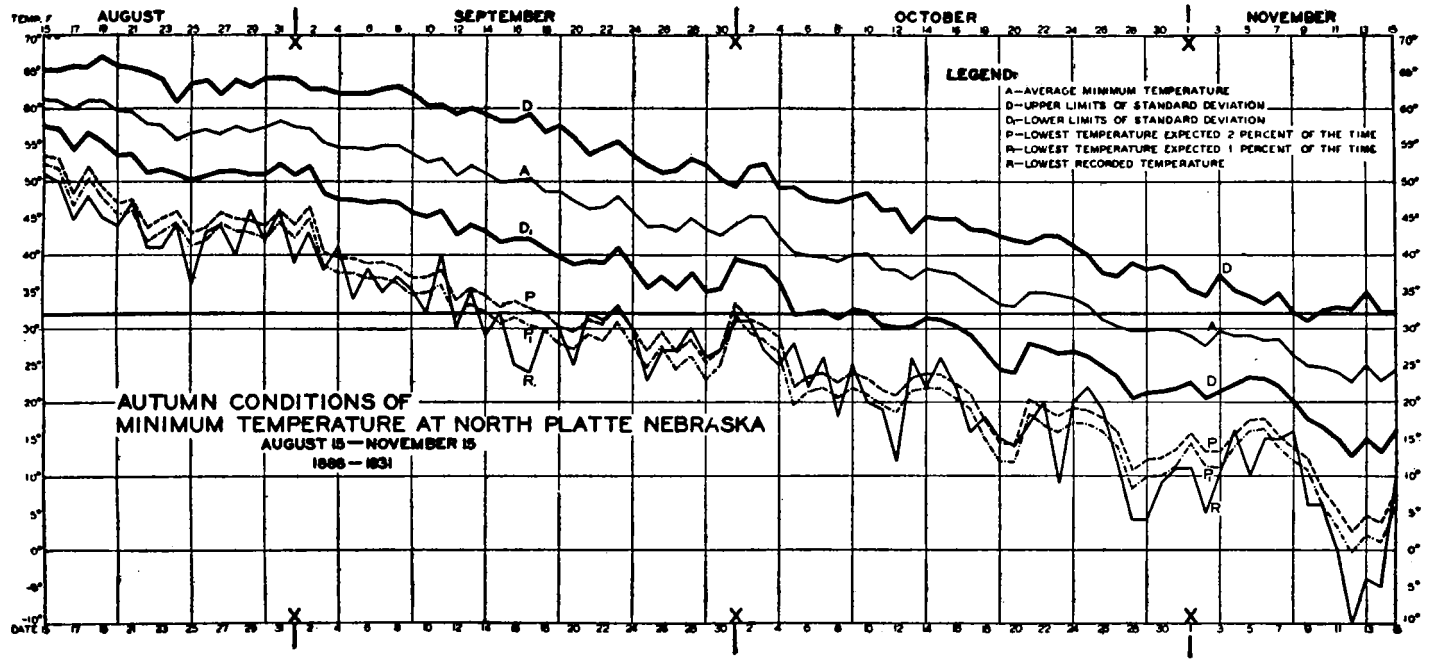

FIGURE 8.

The probability of a killing frost after each date in spring and before each date in autumn is shown in figures 3 and 4. This is to be distinguished from the probability on each date given in figures 1 and 2.

The length of the average frost-free season at Lincoln is 179 days, at North Platte 150, and at Scottsbluff 131. The accompanying table is made up of actual as well as theoretical data. The first column gives the average number of frost-free days. Columns 2 and 3 list the number of days in the shortest and longest actual seasons. Columns 4 and 5 represent the shortest and longest theoretical growing seasons. By longest possible growing

Station	Average number of frost-free days	Shortest actual season (days)	Longest actual season (days)	Shortest theoretical season (days)	Longest theoretical season (days)
Lincoln	179	150	219	124	230
North Platte	150	106	196	99	200
Scottsbluff	131	106	151	85	178

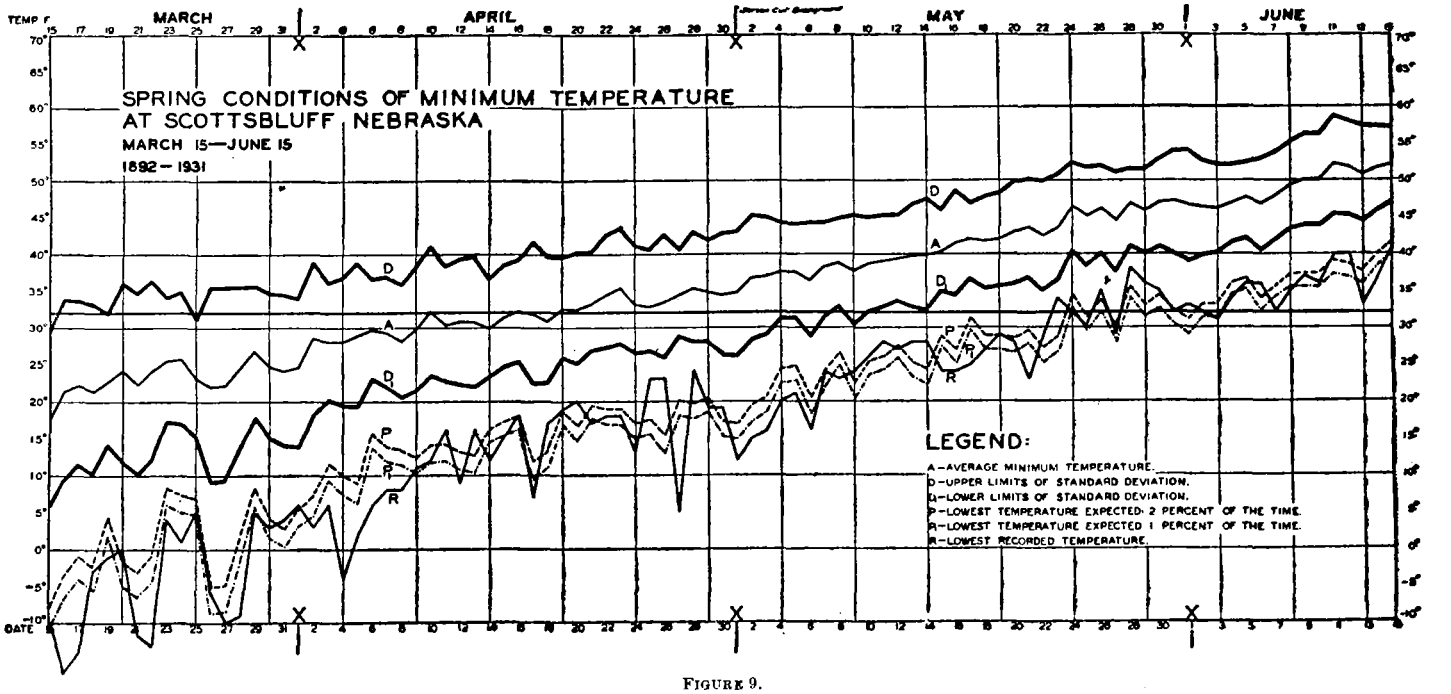

FIGURE 9.

season is meant the length of time between the date of the earliest last killing frost expected 1 percent of the time in the spring and the latest first killing frost in autumn

Thus it can be seen that the average growing season at Scottsbluff begins nearly 3 weeks later and ends nearly 3 weeks earlier than at Lincoln. The variations from the

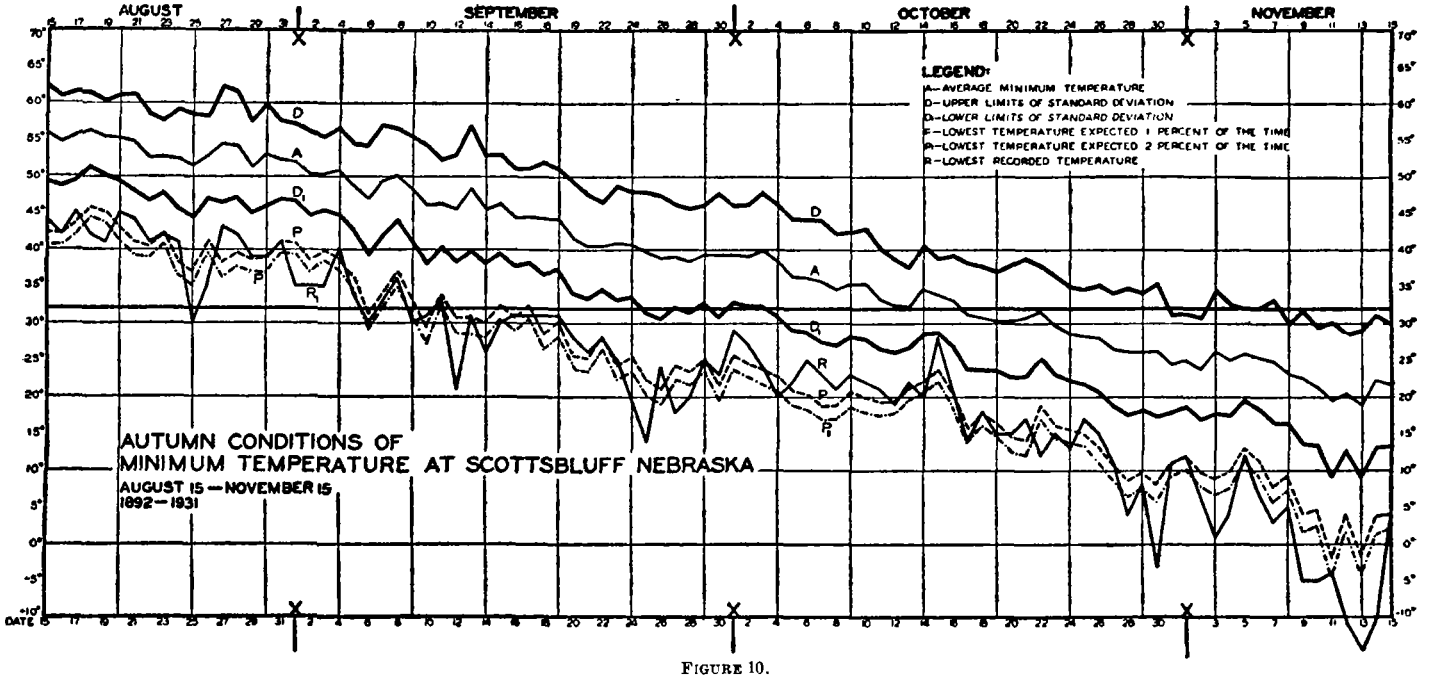

FIGURE 10.

that would likely occur 1 percent of the time. It is obvious that a season as long as this, or as short as between the latest possible and earliest possible autumn freeze, would be a rarity.

average or the unreliability of the frost-free season is greatest at Scottsbluff and least at Lincoln even though the standard deviation of minimum temperature is less at Scottsbluff than at North Platte or Lincoln.